Physiotherapy Theory and Practice

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Online Publication Date: 01 September 2008

To cite this Article Saywell, Nicola and Taylor, Denise(2008) 'The role of the cerebellum in procedural learning—Are there implications for physiotherapists' clinical practice?', Physiotherapy Theory and Practice, 24:5, 321 — 328

To link to this Article: DOI: 10.1080/09593980701884832

URL: http://dx.doi.org/10.1080/09593980701884832

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The role of the cerebellum in procedural learning—Are there implications for physiotherapists’ clinical practice?

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Motor learning is the means by which we acquire skilled movements and consign them to permanent memory. Multiple brain areas are involved, and patients with neurological damage often experience difficulty when attempting to relearn previously learned skills. For these patients, the location of the lesion may be critical in influencing their motor skill relearning. The cerebellum has been described as an “on-line” comparator and corrector of movement, but recent research suggests that the cerebellum may also have a role in the later stages of motor learning, including the automation of movement patterns, although conflicting research in this area means that there is as yet no consensus. This knowledge may have implications for the way physiotherapists treat patients with cerebellar lesions. Some treatments in regular use by physiotherapists are discussed, and possible implications for practice are considered.

Introduction

Physiotherapists working in the area of neurological rehabilitation have been profoundly influenced by motor learning principles. Carr and Shepherd (1982) focused on the physiotherapist’s role as a teacher of functional movements, using environments and activities designed to replicate a patient’s daily life. The aim was to facilitate learning, by maximising cognitive engagement in a task. The discovery of cortical plasticity as a response to repetition and practise of volitional and meaningful tasks has helped influence physiotherapy (Bayona, Bitensky, and Teasell, 2005; Hikosaka, Nakamura, Sakai, and Nakahara, 2002; Sanes and Donoghue, 2000).

To learn new motor skills, procedural memory is required. Procedural memory encodes the “procedures” involved in a task (Hikosaka et al, 1999). This differs from declarative memory, which stores the “what to do” or the facts relating to a task. Therapists utilise both memory types when treating patients, but procedural memory will be the focus of this paper.

The role of cortical structures in motor learning is widely acknowledged (Ioffe, Ustinova, Chernikova, and Kulikov, 2006; Muellbacher et al, 2001; Sanes and Donoghue, 2000) and with advances in neuroimaging techniques, areas of the brain involved in specific functions have been able to be studied in detail (Grafton, Hazeltine, and Ivry, 1995; Tesche and Karhu, 2000). The basal ganglia and the cerebellum have been recently recognised as having an important role in motor learning. However the cerebellum’s role has been particularly controversial (Miall and Reckess,
2002; Nixon, 2003), with some research finding no increase in cerebellar activity during procedural learning (Grafton, Hazeltine, and Ivry, 1995) and some finding the cerebellum active at differing stages of the learning process (Flament et al, 1996; Lang and Bastian, 2002). Studies investigating aspects of motor learning will be considered in more detail, and implications for physiotherapists treating patients with cerebellar lesions will be extrapolated from current literature.

Motor learning

Based on the three-stage model of motor learning described in 1967 by Paul Fitts and Michael Posner (Magill, 1993) during the initial, cognitive stage of learning, there is a strong reliance on sensory feedback (Nixon, 2003), movements tend to be uncoordinated (Thach, 1998), and errors are usually of large magnitude (Coker, 2004). In the second, associative stage, the skill has to some extent been learned but still requires significant cognitive control. At this stage the brain needs to be able to utilise feedback in a predictive manner to become more skilled. Both the spatial and the temporal aspects of each movement must be detected and compensations made to refine the basic movement pattern of the previous stage (Nixon and Passingham, 2001). In the final, autonomous stage of motor learning, the skill becomes automatic and requires less attention, error correction will be of small magnitude, and the skill will be transferable to different environments (Magill, 1993).

The permanence of this last stage of skill acquisition has made it a desired and yet often frustratingly elusive goal for physiotherapists and their patients with brain injury and disease. The knowledge of how a movement is to be performed and the processes required to achieve the autonomous level of learning requires multiple brain areas (Boyd and Weinstein, 2004; Lalonde and Strazielle, 2003) including the cerebellum.

Role of the cerebellum in motor learning

The cerebellum is often described in the literature as a comparator, which detects and corrects errors in movement (Coker, 2004). It has afferent connections with virtually every sensory system in the body (Molinari, Filippini, and Leggio, 2002). So, during movements in which there is time to perceive a sensory signal and make the appropriate adjustments, the cerebellum adjusts the movement in response to the sensory afferents (Tesche and Karhu, 2000). This implies a reactive role, with the cerebellum having a motor control, rather than a motor learning function (Chafetz, Friedman, Kevorkian, and Levy, 1996).

Recent evidence suggests complex roles for the cerebellum in motor learning. These roles fall into two main categories: 1) skill acquisition and refinement encompassing a continuum from the cognitive, through the associative stages of learning (Boyd and Weinstein, 2004; Molinari et al, 1997; Petrosini et al, 2003) and 2) skill automation and retrieval, which correlates well with the autonomous stage of learning (Nicolson et al, 1999; Nixon and Passingham, 2001).

Skill acquisition and refinement

Sensory prediction

A recurring theme in the literature regarding the role of the cerebellum in motor learning is that of a predictor of the sensory consequences of motor activities. Magneto-encephalography (MEG) has revealed that, unlike the primary sensory cortex that only responds to a sensory stimulus, the cerebellum has an additional role. Tesche and Karhu (2000) found that the cerebellum responds to a sensory stimulus, but if the sensory stimulus is perceived to have a temporal regularity, it responds in an anticipatory manner at the time the next stimulus might be expected, implicating it in pattern recognition (Molinari et al, 1997; Nixon, 2003). The formation of an internal “feed forward” model, with the ability to predict sensory information, allows cerebellar efferent output to the motor cortex prior to movement, thereby reducing the number of reactive corrections necessary once movement has begun (Matsumura et al, 2004; Nixon, 2003).

In addition to anticipating sensory stimuli that have temporal regularity (Tesche and Karhu, 2000), the cerebellum also modulates afferent information to block extraneous information that
may confound appropriate response to meaningful information (Blakemore, Frith, and Wolpert, 2001). An illustration of this is the difference between a self-generated skin tickling sensation and one from an external source (Nixon, 2003). In one experiment on normal human subjects, the intensity of a tickling sensation on the hand was investigated, comparing a self-generated tickle with a robotically generated one (Blakemore, Wolpert, and Frith, 1998). It was consistently shown that the congruency between the motor action and the resultant sensation reduced the stimulatory capacity of the sensation. So during self-generated tickling movements the cerebellar activity decreased, whereas externally generated tickling significantly activated the cerebellum. This implicates the cerebellum in the function of holding an afferent copy of a motor command and its likely sensory consequence, and then comparing that to actual sensation (Blakemore, Frith, and Wolpert, 1999). This allows sensations that are the result of predicted self-generated movements to be filtered out to allow focus on the novel or unpredicted inputs important for learning.

Role of visual input

Sensory stimuli that are not self-generated, but externally generated, utilise afferent cerebellar pathways but, if they are not associated with any movement, could they still result in motor learning and effect some subsequent cortical changes? In other words, can motor learning take place from watching the performance of a task?

During the acquisition phase of learning, visual afferent information associated with observation of task performance without any corresponding motor activity has been shown to involve the cerebellum. In an experiment by Petrosini et al. (2003), rats were suspended in a cage above a water maze and observed trials of other rats finding a platform hidden in the maze. Once the suspended rats were released into the water maze, they escaped more quickly than rats that had not observed, perhaps using strategies learned during observation. Some of the suspended rats were given a cerebellar lesion prior to the observation and showed no evidence of having learned from the observation. If the cerebellar lesion was performed after the observation, the rats retained the strategies for exploration that were learned preoperatively. However, the rats that retained the preoperative escape strategy appeared unable to modify the learned skills in response to environmental changes, which further supports the importance of the cerebellum in acquiring new procedural learning, rather than accessing prelearned strategies.

Effect of attention

A further variable in the cerebellum’s response to sensory stimulation is the degree of focussed attention a person gives to the stimulus. Tesche and Karhu (2000) found that both the primary sensory cortex and the cerebellum have a strongly suppressed reaction to sensory stimulation when the experimental subject is reading a book and therefore not attending to the stimulus.

Lang and Bastian (2002) investigated the influence of a secondary task on the performance of a well-learned motor task. The well-learned task was a continuous figure-8 movement around two flexible barriers with a baton held in the hand. The secondary task was an auditory vigilance task, requiring concentration on a sequence to give information about it at its completion. Cerebellar patients were able to improve the performance of the motor task, but the addition of a secondary task degraded the performance to prepractise levels. Control subjects were able to maintain their motor performance during the secondary task. The possibility that it was simply a motor performance problem was controlled for by trialling the cerebellar patients on a simplified motor task, which was performed easily in isolation. The same result occurred when the secondary task was added. The implication is that the patients with cerebellar damage have significantly increased demands on the central executive areas of the brain involved with attention and that very little is able to be automated (Lang and Bastian, 2002).

In case studies of two patients with impaired cerebellar function (Chafetz, Friedman, Kevorkian, and Levy, 1996), it was noted that in the patient with a right cerebellar infarction, attention to a task was poor and the patient was easily distracted. In the patient with a left cerebellar stroke, there was evidence of his attention being diverted to
alternative stimuli to the ones useful for the current task. Both patients displayed an inability to attend to a given task. This finding concords with the previous evidence that the cerebellum is active in gating unwanted information (Nixon, 2003).

The cerebellar lesion makes it more difficult to attend to a task, and this reduction in attention further reduces activity in the cerebellum. These two impairments may have a cumulative effect on a patient’s ability to remain focused on a task.

Utilising sensory information in motor learning

A further step in investigating the role of the cerebellum is to study its role in not just predicting sensory events but changing motor performance and skill acquisition as a consequence of that prediction. The ability to respond to predictable events, both quickly and accurately is one hallmark of a learned movement.

Boyd and Weinstein (2004) conducted a comparison study of patients with cerebellar stroke and age-matched volunteers to look at the precise aspect of motor learning most affected by cerebellar lesion. Participants performed a unilateral tracking task with the contralesional limb to determine whether temporal or spatial accuracy of performance was affected. Spatial accuracy of motor response was found to be unaffected in cerebellar patients, but they were unable to improve temporal accuracy, by reducing reaction time, compared with normal subjects. Using the contralesional limb allowed the learning component of the task to be more easily separated from the motor performance aspect, as cerebellar impairments such as intention tremor and dysmetrias usually affect the ipsilesional limb (Ghilardi et al, 2000), whereas the difficulties encountered in procedural learning have been shown to be effector nonspecific (Molinari et al, 1997).

Balance and gait

Despite the considerable evidence of motor learning displayed in visual tracking tasks, for a majority of patients, this is not representative of the activity of most concern. For a large proportion of patients seen by physiotherapists, the ability to stand and ambulate independently is of primary importance.

A study was undertaken to compare gait control in patients with cerebellar lesions with age- and sex-matched controls. The ability to select appropriate motor strategies in response to sudden changes in treadmill speed was investigated. All the subjects with cerebellar lesions were able to ambulate independently at the same speed as the controls. The control subjects demonstrated a rapid acquisition of an efficient and consistent motor strategy in response to the change in treadmill speed. The duration of muscle activity decreased with practise, and muscle onset occurred in a pattern almost identical to normal gait. The subjects with cerebellar lesions did use an altered stepping strategy; however, this was neither similar to the controls nor consistent. The variability of onset times and duration of muscle activity persisted during all 60 trials. One of the characteristics of a learned movement is that it has consistency from one performance to the next. The lack of any consistent stepping strategy suggests that motor learning was not taking place (Rand et al, 1998).

In a study by Earhart and Bastian (2001) comparing the strategies used by cerebellar patients when stepping on varying sizes of inclined wedge, it was noted that there were considerable variations in strategy for cerebellar patients between different angles of wedge. Although this wasn’t strictly a motor learning study, the inability to modify a strategy and apply it consistently points to the cerebellar patients’ loss of movement adaptability. However, the basic motor pattern was still present, which is consistent with the contention that the cerebellum is not required to access motor programmes but assist in new learning to refine them for specific environments.

Skill automation and retrieval

The cerebellar effect on the cerebral cortex is highly dependent on Purkinje cells. The deep cerebellar nuclei have a facilitatory effect on motor cortical activity, but the cortical Purkinje cells can inhibit the nuclei; therefore, dependent on the relative activity of the deep nuclei or the cerebellar cortex, there can be either a net facilitatory or net inhibitory effect on motor cortex excitability. The cerebellothalamiccortical pathway is one proposed route via which contextual
information may be delivered, altering the synaptic efficiency of interneuronal connections in the motor cortex (Molinari, Filippini, and Leggio, 2002). The balance of excitatory and inhibitory influence on the motor cortex is implicated in shaping plastic cortical change. Once cortical change takes place, movement relies much less on sensory stimulus to guide it, instead relying on a preplanned sequence of motor coordinates to execute a smooth, effortless performance. In this way as a task becomes more automatic, it is less reliant on external feedback.

Furthermore, the vast quantity of sensory feedback generated by quick, well-coordinated movements must be gated in some way to allow the automated movement to continue without the time delay that processing the sensory information a complex movement would generate. The cerebellum with its dual skills of predicting and recognising an established pattern and being able to inhibit sensory reafference is ideally suited to allowing a minimum of self-generated interference during automatic actions (Nixon, 2003).

Well-learned motor behaviours don’t seem to be stored in the cerebellum (Rand et al, 1998); the most likely site of storage of both procedural and declarative memory is the cerebral cortex (Molinari et al, 1997). However, the cerebellum is acknowledged to have a role in consigning memories to permanent storage. The basal ganglia also have a considerable role during activities where movement changes are related to reward, but the cerebellum’s unique role appears to be in the ability to distinguish sensory patterns and adapt in an anticipatory manner to produce appropriate motor strategies (Nixon, 2003).

In a study of normal adults, using positron emission tomography (PET), cerebellar involvement in a procedural motor task was investigated. The conditions during investigation were rest, performing an overlearned finger-tapping sequence and learning a new finger-tapping sequence. There was significant activation of the cerebellum in the new task, but there was also a moderate level of cerebellar activation in the overlearned condition. The author’s conclusion was “that the cerebellum is involved in the process by which motor tasks become automatic” (Nicolson et al, 1999). The other equally plausible conclusion is that the cerebellum is required to access well-learned movements from permanent storage. This latter conclusion, however, is given less weight by Matsumura et al. (2004), who found that the left lateral and parasagittal cerebellum, which were the areas of the cerebellum that were active during a novel task, showed a gradual decrease in activity as actions became more automatic. The difference in findings may be accounted for by the length of time since skill acquisition. The fact that these areas showed “gradual decrease in activity as learning proceeded” (Matsumura et al, 2004) implies prolonged practise of a task leading to reduced cerebellar activation, whereas Nicolson et al. (1999) was citing a study by Jenkins et al. (1994), in which the sequence was learned during the period just prior to neuroimaging. Luft and Buitrago (2005) agree that the degree of motor experience can lead to conflicting neuroimaging findings between similar stages of motor learning.

Implications for practise

Considerable difficulties are encountered when extrapolating information from animal models to humans with cerebellar lesions. Animals with the cerebellum removed are often used in research, giving information of mammalian behaviour without any cerebellar input. However, it is unusual in humans to find a complete absence of cerebellar activity and even more unusual to find it in isolation. Researchers studying cerebellar function in humans often use patients with common degenerative diseases affecting the cerebellum such as multiple sclerosis and olivopontocerebellar atrophy (OPCA). These diseases affect other areas of the brain as well, but they do have more practical similarities with patients being seen by many physiotherapists. A cerebellum that is functioning suboptimally and a central nervous system with multiple areas of damage are commonly encountered presentations in clinical practise.

Studies investigating the effect of discrete areas of damage to the cerebellum in humans have been undertaken. One such study evaluated serial reaction times following removal of a benign posterior fossa tumour in children and adolescents (Berger et al, 2005). This study revealed similar motor learning to normal subjects, which is markedly different from patients with more widespread degenerative changes. This may indicate that discrete cerebellar loss can be compensated for by other areas of the
brain in this young age group, when plastic changes occur more readily. However, an inability to modify learned behaviour in response to a new challenge was noted. In contrast, Molinari et al. (1997) found that adult subjects with focal cerebellar lesions had significantly impaired procedural learning compared with control subjects, when undertaking a visuo-motor task.

Despite the range of subjects used in experiments to understand the role of the cerebellum in procedural learning, a recurring theme becomes evident. There is substantial evidence that cerebellar damage impairs procedural learning during both the early and later stages of motor learning. This finding may have some practical application in the treatment of patients with cerebellar damage or dysfunction.

**Utilising declarative memory**

A procedural memory formed during a motor task often becomes declarative during the learning process. The consistency of practice allows the participant to gain knowledge of the movement that can be verbalised (Molinari, Filippini, and Leggio, 2002). Neuroimaging evidence shows that declarative learning uses different areas of the brain, primarily the medial temporal lobe memory system, including entorhinal, perirhinal, and parahippocampal cortices (Squire and Zola, 1996), and the cerebellum’s role is significantly reduced when the type of memory used is declarative. For a patient with a cerebellar lesion, the areas of brain unaffected by the damage could therefore be utilised during treatment to compensate for the loss of procedural learning; declarative learning techniques could allow better retention of information. A patient who is asked to repeat a sequence verbally until it is easy to recall will be utilising intact areas of the brain. Molinari et al. (1997) demonstrated that patients with a focal cerebellar lesion exhibited significantly longer reaction times than normal controls when tested on a predictable sequencing task. Once the knowledge of the sequence was acquired declaratively, the cerebellar patients performed with significantly decreased reaction times. The cerebellar patients were far less adept at gaining declarative knowledge secondary to doing the task than were the control subjects. However, Petrosini et al. (2003) notes that once declarative knowledge has been gained, it can assist in the acquisition of procedural knowledge. This solution has benefits and limitations. Declarative knowledge by its nature degrades more easily than procedurally gained knowledge, which means that learning will need more constant refreshment. The performance of tasks also tends to be slower as cognitive control is exerted; however, because it is easier to teach a declarative sequence than a procedure, relatives and caregivers may be more willing and more able to assist in the teaching process. Learning that is acquired declaratively is also more able to be put together in short sequences, which are less dependent on order than procedurally learned tasks (Hikosaka et al, 1999). In a practical setting, to teach the task of sitting to standing, the sequence will need to be broken into steps, with clear instructions, such as “nose over toes.” A short verbal sequence is required to enable the declarative learning of each submovement; this will enable the task to be used in mental rehearsal more readily than a task acquired procedurally (Shumway-Cook and Woollacott, 2007).

**Using visual feedback**

The role of the cerebellum is to integrate information and allow a congruent picture to develop; in a cerebellar lesion this may not happen effectively (Leggio et al, 1999), and sensory stimuli that are incongruent can cause significant difficulty. It is not uncommon for physiotherapists to augment visual feedback using a mirror to assist a patient’s spatial orientation. However, because the visual information is a mirror image of reality, this will conflict with proprioceptive information relayed to the cerebellum (Sanes, Dimitrov, and Hallett, 1990). The mirror image may confuse the internal representation of a movement or posture. Observational learning or modelling is one of the most common strategies for teaching a new skill. In treatment sessions physiotherapists are commonly taught to demonstrate the skill first (Magill, 1993). Carr and Shepherd (1999) indicate that individuals often benefit from demonstration of an action to correct an action in a specific plane of motion. For example, in moving from a sitting to a standing position, patients frequently fail to transfer their weight sufficiently over their base of support. Demonstration of a sagittal plane view is
thought to assist in the patients understanding of the faulty movement pattern. It has been shown that the cerebellum has an active role in assisting the acquisition of skills by observation and this, in patients with cerebellar lesions, may prove an ineffective tool in assisting learning.

Utilising premorbid skills

Cerebellar activation appears to be related more to the novelty of a task than its difficulty and cerebellar activity decreases once a difficult task had been well learned. The subsequent retrieval of the memory from storage does not appear to necessitate significant cerebellar activity.

There is evidence to suggest that motor skills learned prior to a cerebellar lesion may still be accessible to a patient (Petrosini et al, 2003), whereas learning previously unknown skills, especially in a foreign environment, may be much harder to achieve. Gaining an insight into the patient’s previous functional level and physical activity level is always an essential component of a physiotherapy assessment, but it may take on special significance to gain clear specific information about tasks that were previously well learned and automatic. Moving from lying to sitting, sitting to standing and gait will all have been achieved premorbidly from furniture and wearing clothing and footwear that can be identified and approximated. Hobbies, sports, and interests that utilised specific gross or fine motor skills, such as bowls, chess, tennis, or woodwork, can be investigated for motor sequences that could be generalisable to other daily activities. These motor sequences may be able to form the basis of treatment, reducing the amount of new motor learning required. In addition, knowing that attention to task is important, yet difficult to achieve for these patients, the level of motivation is vitally important in regaining skills. Therefore, a previously enjoyed activity or important functional goal will increase the engagement in the task and therefore the likelihood of success. A goal of returning to a role, such as collecting the paper from the letter box, engenders more attention than a similar distance covered with no specific goal in mind (Shumway-Cook and Woollacott, 2007). It has been shown that the basal ganglia are active during reinforcement learning, where there is an increased likelihood of reward, so the goal-focused approach may also maximise the use of compensatory brain areas to maximise learning (Ioffe, Ustinova, Chernikova, and Kulikov, 2006).

Environmental factors may also make a home-based treatment programme a desirable goal in this group of patients. Evidence (Berger et al, 2005) suggests that patients with a cerebellar lesion may be able to compensate for unfamiliar tasks and settings, but that this requires significant and sustained cognitive effort, which will certainly reduce the amount of extra information able to be processed.

Conclusion

The function of the cerebellum has been evaluated in light of emerging evidence; increased understanding has given rise to theories about the role of the cerebellum in motor learning. Animal and human studies, of both normal and lesioned individuals, have added evidence with significant consensus regarding the role of the cerebellum in sensory pattern recognition and the ability to compare expected with actual sensory outcome of movement. The evidence of implicit learning deficits in patients with cerebellar lesions gives weight to the theoretical models proposed. The main implication for practise drawn from the theoretical models is that strategies to facilitate motor learning may need to be altered or adapted in this patient group to avoid impeding progress.

References
